Fractional quantum Hall effect without energy gap

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In the fractional quantum Hall effect regime we measure diagonal (ρ_{xx}) and Hall (ρ_{xy}) magnetoresistivity tensor components of two-dimensional electron system (2DES) in gated GaAs/Al$_x$Ga$_{1-x}$As heterojunctions, together with capacitance between 2DES and the gate. We observe 1/3- and 2/3-fractional quantum Hall effect at rather low magnetic fields where corresponding fractional minima in the thermodynamical density of states have already disappeared manifesting complete suppression of the quasiparticle energy gaps.

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Energy gaps in the quasiparticle excitation spectrum play important role for explanation of both integer and fractional quantum Hall effects (QHE) in the most of theoretical constructions (for review see Ref. [1]). However, for the integer QHE only the mobility gap is required [2] which in general may appear in the absence of the energy gap. Existence of the integer QHE without Landau quantization and corresponding modulation of electron density of states has been predicted [3] on the base of the scaling approach for the case of low magnetic fields ($\omega_c\tau \ll 1$, where ω_c is the cyclotron frequency and τ is the electron relaxation time) when the cyclotron energy gaps are completely suppressed by disorder. This effect has not been found so far, probably, because of extremely low temperatures required for its manifestation [4]. However, the observation of the integer QHE in thick heavily Si-doped n-type GaAs layers with three-dimensional energy spectrum in the extreme quantum limit of applied magnetic field [5], strongly supports the idea that the integer QHE is not necessarily related to the energy gap. Since the scaling treatment of both integer [3, 6] and fractional [7, 8, 9, 10] QHE relies on the values of magnetoconductivity tensor components irrespectively to features of quasiparticle energy spectrum a question arises: is the fractional QHE possible in the absence of the energy gap by analogy with the integer QHE? More specifically, the question addressed in this paper is whether a disorder, which is known to suppress the fractional QHE and the energy gap, suppresses them simultaneously or the energy gap completely vanishes before the fractional QHE (and the mobility gap of quasiparticles) disappears.

Here we present experimental data that indicate that the fractional QHE can survive in a rather weak magnetic field where the fractional features in the energy spectrum have already vanished. In the fractional QHE regime, we measure diagonal (ρ_{xx}) and Hall (ρ_{xy}) magnetoresistivity tensor components of two-dimensional electron system (2DES) in gated GaAs/Al$_x$Ga$_{1-x}$As heterojunctions, together with capacitance between 2DES and the gate. Inverse value of the capacitance per unit area C depends linearly on $d\mu/dn$ [11], the inverse value of the thermodynamical density of states (here n is the areal electron density and μ is the chemical potential of 2DES). The energy gap leads to a jump of the chemical potential μ at a fractional filling factor [12] and, therefore, to a peak in $d\mu/dn$. This peak has been found in experiments on electric field penetration through 2DES [13] and capacitance measurements [14]. Vanishing of the peak implies disappearance of the corresponding minimum in the thermodynamical density of states, i.e., collapse of the energy gap.

We study two gated samples produced from two different wafers with single remotely doped GaAs/Al$_x$Ga$_{1-x}$As heterojunction. They have an undoped Al$_x$Ga$_{1-x}$As spacer of 70 and 40 nm width and the distance between the gate and the heterojunction is 580 and 110 nm for sample 1 and 2, respectively. At zero gate voltage, the samples had electron densities $n_1 = 1.4 \times 10^{11}$ and $n_2 = 1.8 \times 10^{11}$ cm^{-2} and mobilities $\mu_1 = 1.2 \times 10^6$ and $\mu_2 = 6.8 \times 10^5$ cm^2/Vs. The density varies linearly with the gate voltage practically down to the point of complete depletion of 2DES. The Hall bar geometry is used to measure the Hall and diagonal resistivities. To measure capacitance the gate voltage V_g is modulated by low frequency (7-9 Hz) ac voltage and the two components of ac current between the gate and 2DES are measured. The component shifted by 90° relative to the modulation voltage is proportional to the capacitance. To obtain correct amplitude and width of the fractional peak, we use the modulation amplitude below 15 and 4 mV for sample 1 and 2, respectively. The in-phase component appears only at very low values of σ_{xx} due to the resistive effects in 2DES [15]. These effects prevent charging of 2DES and lead to a drastic decrease of the out-of-phase current component. To measure capacitance in the fractional QHE regime accurately it is necessary to have values of σ_{xx} that are not too small, which sets a lower limit on the temperature of measurement depending on the magnetic field value. Just above this limit, temperature dependence of the capacitance is weak, so the peak amplitude measured at such conditions is expected to be close to the amplitude at zero temperature. Note, that in the range of magnetic field that is of special interest for us, where the energy gap and QHE successively disappear, the measurements are limited from below by the lowest temperature we can achieve.

Experimental results for sample 1 are shown in Fig. 1

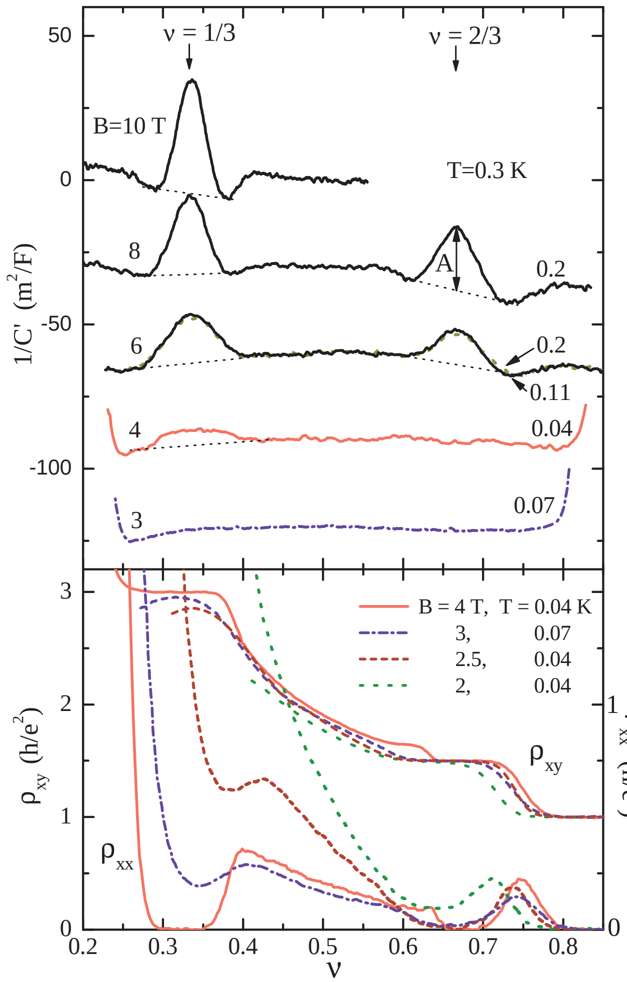

FIG. 1: (color online). (upper panel) Variation of the inverse capacitance $1/C' = 1/C - (5568 - 90\nu)$, and (lower panel) the diagonal (ρ_{xx}) and Hall (ρ_{xy}) resistivities (both given in units of h/e^2) versus filling factor ν tuned by the gate voltage V_g at different magnetic fields and temperatures, shown in the figures, for sample 1. The capacitance curves measured at different magnetic fields are vertically shifted, the left scale corresponds to 10 T curve. Dotted straight lines in upper panel were used as baselines for determining peak heights A.

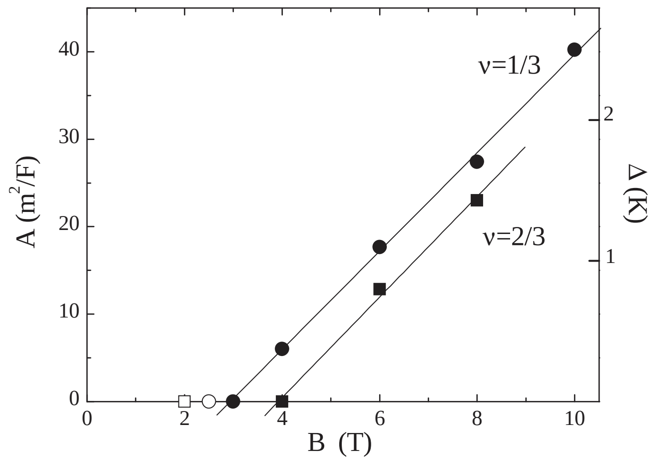

FIG. 2: Amplitude of the peaks A in the inverse capacitance $1/C$ as a function of magnetic field (solid symbols). Open symbols show minimal field values where development of the fractional QHE is observed. Estimation of the gap values are shown by the right scale.

as a function of filling factor $\nu = nh/eB$, tuned by the gate voltage. The upper panel shows how the peaks in the inverse capacitance related to energy gaps in the 1/3- and 2/3-fractional QHE states damp with decreasing magnetic fields. In order to stress peaks in $1/C(\nu)$ linear function of ν with the slope of -90 m^2/F is subtracted from all experimental data and resulting curves are shifted vertically for clarity. The data are measured under conditions at which resistive effects do not affect the results yet, but temperature dependence of the capacitance is already weak. It is illustrated by comparison of curves measured in 6 T field at 0.11 K and 0.2 K. This supports our expectations that the magnetocapacitance data approximately reflect their zero-temperature behavior. In the lower panel, the diagonal ρ_{xx} and Hall resistivity ρ_{xy} are shown. Comparison of the magnetocapacitance and magnetotransport data for $B = 4$ T and $T = 0.04$ K clearly shows that a well-developed QHE exists at $\nu = 2/3$ while the corresponding peak on the magnetocapacitance curve at $\nu = 2/3$ is absent. Moreover, the QHE features in the magnetotransport survive down to substantially lower magnetic fields (2 T). This is the key observation which indicates the existence of QHE at $\nu = 2/3$ in the absence of the energy gap. Similarly, the 1/3-QHE peak on the capacitance curves disappears at $B = 3$ T [16] while QHE features are observed at $B = 3$ T and even at 2.5 T in the magnetotransport data. The amplitudes of the peaks (determined as shown in Fig. 1) as a function of the magnetic field (see Fig. 2) follow straight lines that go to zero at threshold magnetic fields, and QHE is still observed below the thresholds. The energy gaps Δ can be estimated [17] from the peak areas S in Fig. 1. Corresponding values are given by the right axis in Fig. 2.

Fig.3 shows $\delta(1/C) = 1/C(B, V_g) - 1/C(B = 0, V_g)$ (upper panel), ρ_{xx} and ρ_{xy} (lower panel) as a function of the inverse filling factor $1/\nu = eB/nh$ varied by sweeping magnetic field at different electron densities for sample 2. At the largest electron density ($n = 12.4 \times 10^{14}$ m^{-2}) $\delta(1/C)$ shows a well-pronounced peak at $\nu = 1/3$ and weak peak at $\nu = 2/3$ which are not affected by the resistive effects in contrary to the huge peaks at integer filling factors. Strong rise of the $\nu = 1/3$ peak at $n = 8.7 \times 10^{14}$ m^{-2}and $T = 0.08$ K occurs due to the resistive effects and is accompanied by appearance of a peak in the in-phase current component which constitutes about 10% of the total capacitive current. The 1/3 peak in $\delta(1/C)$ completely disappears at $n = 5.4 \times 10^{14}$m^{-2} while well developed Hall plateau and deep minimum in the magnetoresistance are still observed. Similar behavior is observed for $\nu = 2/3$ where the peak disappears at

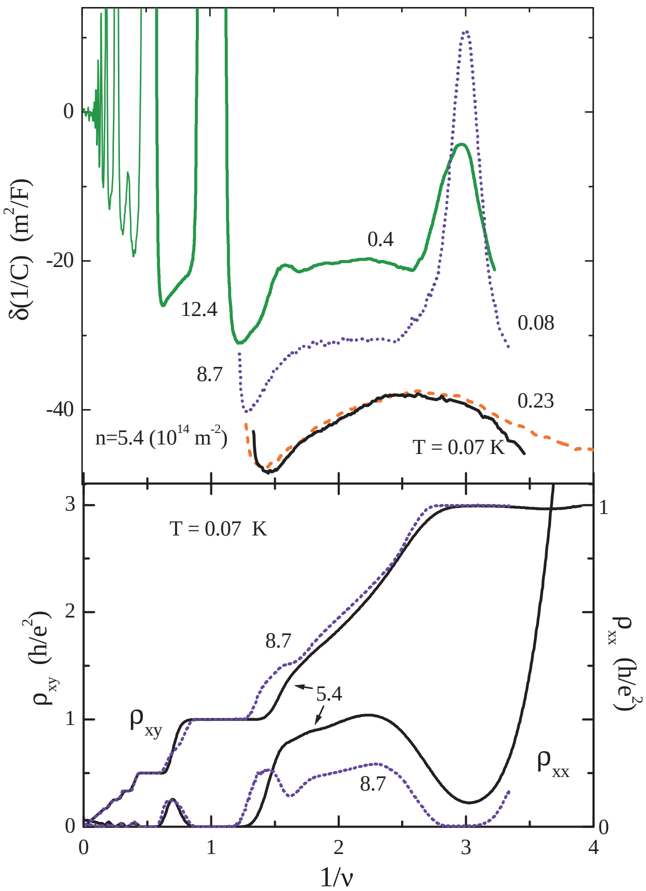

FIG. 3: (color online). (upper panel) Variation of the inverse capacitance $\delta(1/C) = 1/C - 1/C_{B=0}$ and (lower panel) magnetotransport data for sample 2 versus the inverse filling factor varied by magnetic field for different electron densities n (in units 10^{14} m^{-2}) and temperatures (in K) shown in the figures. $\delta(1/C)$-curves for different electron densities are shifted vertically for clarity. The left scale corresponds to $n = 12.4 \times 10^{14} m^{-2}$ curve. The total inverse capacitance value $1/C \approx 1300$ m^2/F.

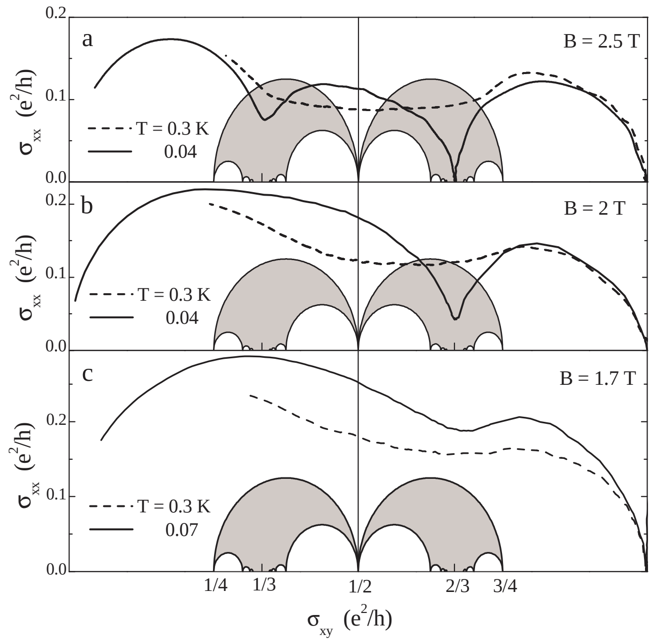

FIG. 4: Magnetotransport data representation in the $\sigma_{xy} - \sigma_{xx}$ plane. Theoretical regions of conductivities converging to the 1/3- and 2/3- fractional QHE states when temperature goes to zero are shown by left and right grey areas, respectively. The dotted and solid lines present experimental conductivity traces obtained by sweeping gate voltage for $T = 0.3$ K and the base temperature, respectively. The traces in panels (a), (b), and (c) correspond to indicated magnetic fields.

$n = 8.7 \times 10^{14}$ m^{-2} but 2/3-QHE features survive.

Disappearance of the energy gap at a threshold magnetic field is established in different experiments [14, 18] and is attributed to a disorder inevitably present in real samples. The role of disorder in the fractional QHE is a very complicated problem which, at the moment, is only partly addressed on the microscopic level (for the case of the short-range fluctuations of potential see, for example, results of recent numerical calculations [19] and references therein). In the selectively doped GaAs/AlGaAs single heterojunctions, dominating potential fluctuations are generally accepted to have a long-range character because charged impurities are located behind the spacer, which thickness d is larger than the inverse Fermi wave vector. For filling factors smaller than unity this is equivalent to condition that magnetic length $l_B \ll d$. Potential fluctuations lead to electron density fluctuations. Quantitative analysis of $d\mu/dn$ for such heterojunctions was proposed in Ref. [20] in so-called narrow gap approximation. It assumes that characteristic energy $W \sim \sqrt{N_i}e^2/\varepsilon$ of smooth random potential is much larger than the energy gap Δ. Here N_i is the average areal density of charged donors in the doped layer which is close to the areal density of 2D electrons at zero gate voltage and ε is the dielectric constant. When average electron density is close to the value n_f corresponding to a fractional QHE, a sample is expected to be divided into areas of compressible phase with $n < n_f$ and $n > n_f$ separated by strips of incompressible phase with $n = n_f$. In this case, the peaks in magnetocapacitance measurements are related to the incompressible strips, nevertheless, values of the gap that are derived from them are expected to be close to the gap of a pure system $\Delta_p \propto B^{1/2}$ [20]. However, there is additional validity condition of this result: the strip width d_{str} cannot be smaller than the magnetic length l_B. Since $d_{str} \propto \Delta_p^{1/2} \propto B^{1/4}$ and $l_B \propto B^{-1/2}$ condition $d_{str} > l_B$ fails at weak magnetic fields and the incompressible strips should disappear leading to disappearance of the capacitance peak. In this context our observation of different thresholds for the capacitance peaks and for the fractional QHE imply that the presence of incompressible strips is not necessary condition for the fractional quantization. Note that in our case $W \sim 50$ K and condition $W \gg \Delta$ of the narrow gap

approximation is fulfilled in the entire range of magnetic fields in question.

Note that within the composite fermion approach [22], our observation resembles the prediction [3] for the integer QHE. Indeed, the absence of the fractional features in the capacitance data leads to the conclusion that the Landau quantization in the composite fermion energy spectrum is completely smeared out by disorder.

According to the scaling theory, at infinite coherence length, integer and fractional QHE states together with the insulating state produce complete set of possible ground states for 2DES in magnetic field. Particular ground state can be reached only if the magnetoconductivity tensor components at a finite coherence length belong to a respective region in the $\sigma_{xy} - \sigma_{xx}$ plane. The corresponding regions for 1/3 - and 2/3 - fractional quantum Hall effect states [8, 23] are shown in Fig. 4 by grey areas. In these regions, points $(\sigma_{xy},\ \sigma_{xx})$ flow to (1/3, 0) or to (2/3, 0) when temperature goes to zero. These areas are upper-bounded by two semicircles connecting point (1/2, 0) with points (1/4, 0) and (3/4, 0). The semicircles are qualitatively similar to the phase boundaries of Ref. [24] in $\rho_{xy} - \rho_{xx}$ plane. Our experimental data are in good quantitative agreement with the theoretical prediction [8, 23]. If conductivity traces measured with sweeping gate voltage enter the grey areas at $T = 0.3$ K, the base temperature data demonstrate either a well pronounced QHE state (2/3 in Fig. 4a) or a tendency to converge to such state (1/3 in Fig. 4a and 2/3 in Fig. 4b). Otherwise lowering of the temperature results in further deviation of the experimental curves from the grey areas (Fig. 4c and left part of Fig. 4b).

In summary, we have observed the 1/3 and 2/3 fractional QHE under conditions when magnetocapacitance data do not show any sign of the energy gap. Satisfactory quantitative agreement have been found with theoretical values of high-temperature magnetoconductivity tensor components corresponding to disappearance of these fractional QHE states.

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